ENERGY AND MASS BALANCE CALCULATIONS FOR INCINERATORS

C.C. Lee and G.L. Huffman
U.S. Environmental Protection Agency
Risk Reduction Engineering Laboratory
Cincinnati, Ohio 45268

ABSTRACT

An estimate of an energy and mass balance within an incinerator is a very important part of designing and/or evaluating the incineration process. This paper describes a simple computer model which is used to calculate an energy and mass balance for a rotary kiln incinerator. The main purpose of the model is to assist EPA permit writers in evaluating the adequacy of the data submitted by incinerator permit applicants. The calculation is based on the assumption that a thermodynamic equilibrium condition exists within the combustion chamber. Key parameters which the model can calculate include:

- Theoretical combustion air;
- Excess air needs for actual combustion cases;
- Flue gas flow rate; and
- Exit temperature.

INTRODUCTION

Although there are many potential hazardous waste treatment technologies, current data indicate that no other treatment technology is as universally applicable as incineration to treat the many different types of hazardous waste. A recent survey showed that more than 80% of the technologies used to remediate Superfund sites are incineration-related technologies (Lee, 6/90). As a matter of fact, incineration has been considered to be a proven technology in many of the regulations developed under the various environmental laws enacted to cover the treatment/disposal of the different types of solid wastes; for example:

(1) Hazardous, medical and municipal waste as regulated under the Resource Conservation and Recovery Act (RCRA);

(2) Industrial and municipal sludge waste as regulated under the Clean Water Act;

(3) Pesticide waste as regulated under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA);

(4) Superfund waste as regulated by the Superfund Amendments and Reauthorization Act (SARA); and

(5) Toxic substances as regulated under the Toxic Substances Control Act (TSCA).

In addition, incineration facilities are subject to the regulations under the Clean Air Act and numerous State and local requirements.

One of the key factors necessary to ensure the safe incineration of various wastes is for a permit writer to fully understand the incineration process and to adequately check or specify permit conditions at an incineration facility that has come under his or her scrutiny. However, this not an easy task for the following reasons:

- In many cases, the incineration facility is site-specific and process-specific. In other words, different incinerators use different destruction processes and different pollution controls.
- In reviewing a permit application, a permit writer often is confronted with the complex and highly uncertain task of determining whether data submitted are adequate or accurate. For example, if an applicant's data show that his incinerator can reach a certain temperature by burning certain wastes at certain combustion air levels, the question is, "Are the claimed data dependable?"
- In issuing a permit, a permit writer needs to make decisions regarding how to approve or how to specify permit conditions which, for obvious reasons, involve costs and the personnel needed for that industry to comply with the final permit.

The Risk Reduction Engineering Laboratory (RREL) of EPA's Office of Research and Development in Cincinnati has been supporting EPA's RCRA permit writers regarding how to appropriately evaluate a permit application. One of the products from this support effort has been the development of the <u>Energy and Mass Balance Model for Incinerators</u>. The model was intended to assist a permit writer in quickly evaluating whether or not an incineration applicant's claimed data are based on sound engineering principles and are dependable. However, the model involved many complex submodels and are compiled in a computer diskette. Presently, a user cannot see the detailed steps which are built into the software in order to edit the calculation procedures to serve his own specific calculational needs. To overcome this model disadvantage, the authors used the model concept and wrote a program on Lotus 1,2,3 to compare the calculated results with an actual case for which measurement data were available. The results will show that the calculated data are reasonably consistent with the actual trial burn data.

STATEMENT OF THE PROBLEM

A Ciba-Geigy rotary kiln incinerator was chosen as the basis for the calculation. The schematic of the Ciba-Geigy incinerator is shown in Figure 1 (EPA 9/86).

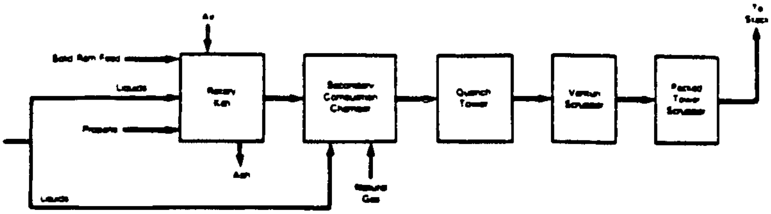

Figure 1. Process Flow Diagram of Ciba-Geigy Incinerator

Ciba-Geigy sponsored a trial burn on November 12-17, 1984. The measured data was later summarized in an EPA report (EPA 9/86) and key aspects of it appear below.

<u>Equipment Information:</u>

- Type of unit: Private incinerator-Rotary kiln with secondary chamber, Vulcan Iron.
- Capacity: 50 tpd (tons per day) with 10% excess capacity (30×10^6 8tu/h for each burner)
- Pollution control system: Quench tower, Polygon venturi scrubber (25-in. pressure drop), and packed tower scrubber.
- Waste feed system:
  - Liquid: Hauck Model 780 wide range burners (kiln and secondary burners)
  - Solid: Ram feed
- Residence time: 5.05 s (kiln); 3.09 s (secondary chamber)

<u>Test Conditions:</u>

- Waste feed data: Hazardous liquid and nonhazardous solid wastes usually burned; for this run, only, synthetic hazardous liquid waste was tested
- Length of burn: 6 to 9 h (2-h sampling time)
- Total amount of waste burned: 480 gal (liquid) and 0 lb (solid)
- Waste feed rate: 4 gpm (liquid); 0 lb/h (solid)

- POHCs (Principal Organic Hazardous Constituents) selected and concentration in waste feed:

Name	Concentration, %
Hexachloroethane	4.87
Tetrachloroethene	5.03
Chlorobenzene	29.52
Toluene	60.58

- Btu content: 15,200 Btu/lb
- Ash content: Not measured
- Chlorine content: 20.8% (calculated)
- Moisture content: Not measured

Operating Conditions:

- Temperature: Range 1750° - 1850°F (kiln); 1950° - 2050°F (Secondary chamber)
- Average 1800°F (kiln); 2000°F (Secondary chamber)
- Auxiliary fuel used: Natural gas
  - Primary kiln 1200 scfh natural gas; Secondary chamber 900-1300 scfh
- Airflow:
  - Primary air to kiln: 2200 cfm
  - Secondary air to kiln: 1400 cfm
- Flue gas oxygen content: 10.3%

ENERGY AND MASS BALANCE CALCULATIONS [For Primary Chamber (Kiln) Only]

a. Given Conditions

a1.	Waste feed rate (gpm):	4 gpm	
	Assume that 1 gal =	5 lb	
	Waste feed rate in lb/hr:		1200 lb/h
a2.	Fly ash (% of waste feed):		0 (assumed)
a3.	% of ash due to unburned carbon:		0 (assumed)
a4.	Ash quench temperature:	undefined	
a5.	Exit temperature:	unspecified	
a6.	Reference temperature:		70°F
a7.	Radiation loss (assumed):	(5%)	0.05 (5%)
a8.	Excess air rate (EAR)[assumed]		0.885 (i.e., 88.5% XSair)
a9.	Humidity at 60% RH and 80°F	0.0132 kg H_2O/kg-dry-air	0.0127 lb H_2O/lb-dry-air
a10.	Standard volume:	24.04 scm/kg-mole	386.9 scf/lb-mole
a11.	Water latent heat:	2460 kJ/kg	1057 B/lb
	Heat capacity (specific heat):		(where B = Btu)
a12.	Ash	0.83 kJ/kg-C	0.25 B/lb-F
a13.	Flue gas:	1.09 kJ/kg-C	0.26 B/lb-F
a14	Water:	2.35 kJ-kg-C	0.49 B/lb-F

a15. 1kcal/g=	4187 kJ/kg	1799 B/lb
	2.33 kJ/kg	1 B/lb
	1 kJ/kg	0.43 B/lb
	1.06 kJ	1 B
	1 m	3.28 ft
a16. Natural gas (NG): (heat of combustion)	13.3 kcal/g	23932 B/lb

	POHC ratio	waste lb/h	ΔHc kcal/g	B/lb	Mixture B/h
Hexachloroethane, C_2Cl_6	0.0487	58.44	0.46	828	4.84E+04
Tetrachloroethene, C_2Cl_4	0.0503	60.36	1.19	2141	1.29E+05
Chlorobenzene, C_6H_5Cl	0.2952	354.24	6.60	11876	4.21E+06
Toluene, C_7H_8	0.6058	726.96	10.14	18246	1.33E+07
Water, H_2O		0		0	
Waste		0		0	
Fuel		0		0	
		0		0	
	1.0000	1200.00			1.76E+07

Therefore, the heat value of the POHC mixture = 14,667 B/lb

a17. Natural gas (NG): 13.3 kcal/g
(heat of combustion)
a18. Total waste heat input: 1.76E+07 B/h

a19. Chemical analysis:

		Σ C's	Σ H's	Σ Cl's	Σ O's	Σ Molecular Weight, M
C_2Cl_6		24.00	0	213	0	237.00
						lb/h
	C's/M	0.1013				5.92
	H's/M	0.0000				0.00
	Cl's/M	0.8987				52.52
	O's/M	0.0000				0.00
		---------				------
		1.0000				Σ = 58.44
C_2Cl_4		24.00	0	142	0	166.00
	C's/M	0.1446				8.73
	H's/M	0.0000				0.00
	Cl's/M	0.8554				51.63
	O's/M	0.0000				0.00
		---------				------
		1.0000				Σ = 60.36
C_6H_5Cl		72.00	5	35.5	0	112.50
	C's/M	0.6400				226.72
	H's/M	0.0444				15.74
	Cl's/M	0.3156				111.78
	O's/M	0.0000				0.00
		---------				------
		1.0000				Σ = 354.24
C_7H_8		84.00	8	0	0	92.00
	C's/M	0.9130				663.72
	H's/M	0.0870				63.24
	Cl's/M	0.0000				0.00
	O's/M	0.0000				0.00
		---------				------
		1.0000				Σ = 726.96

Fuel (natural gas, CH_4) to kiln: 1200 scf/h
Fuel density = Molecular Wt/std volume (a10): 0.04135 lb/scf
Fuel weight flow rate = fuel density x fuel volume flow rate
= 49.62 lb/h

CH_4		12.00	4	0	0	16.00
	C's/M	0.7500				37.22
	H's/M	0.2500				12.40
		--------				------
		1.0000				49.62

H_2O in fuel: 0

a19. Fuel heat input = weight rate x HHV: 1.188+06 Btu/h
a20. Total Heat In = Waste Input (a18) + Fuel Input (a19): 1.88E+07 Btu/h
Total average heating value = a20/(waste + fuel): 15,045 Btu/lb

*****Test data was 15,200 Btu/lb*****

a21. Chemical analysis summary (in lbs/hr):

W & F analysis	F: fuel	unburned carbon	W: waste feed	total combustible feed	Fraction of combustible feed
C:	37.2		905	942.2	0.7540
H:	12.4		79	91.4	0.0731
Cl:			216	216	0.1729
O_2:			0	0	0.0000
N_2:			0		
S:			0		
H_2O			0		
Ash:			0		
Fly ash: (unburned carbon becomes ash):			0		
	49.6		1200	1249.6	1.0000

b. <u>Theoretical Combustion Air</u>

b1. Calculation of oxygen needs
$C+O_2 \text{-->} CO_2$
$O_2=C*32/12=2.67*C= 2.67(942.2)=$ 2516 lb/hr
H left over after Cl's reaction (HLO)
HLO=H-Cl/35.5= 85.32 lb/hr
$H_2+0.5O_2 \text{-->} H_2O$
$O_2=HLO*0.5*32/2=$ 682
$S+O_2 \text{--->} SO_2$ $O_2=S*32/32$ 0
- Bound O_2 0

b2. Theoretical oxygen (Th. O_2) 3198 99.94 mole/h
b3. Th. nitrogen, $N_2=(Th.O_2)*3.76*28/32$ 10521 375.77 mole/h

b4. Theoretical dry air = Theor. O_2+N_2: 13719 475.71 mole/h

b5. Humidity: 0.0127

b6. Water due to humidity = b4*b5 174

b7. Actual theor. air=dry theor. air+its H_2O 13893

b8. Theor. reactants=actual theor. air+feed 15143 lb/hr

b9. Theoretical air combustion products:
$CO_2=C*44/12$: 3455 lb/hr 78.52 mole/h
$SO_2=S*64/32$ 0 0.00

b10. H_2O=HLO*18/2:	768	42.66
N_2=(Th.O_2)*3.76*28/32	10521	375.77
HCl=Cl*36.5/35.5	222	6.08
b11. H_2O in feed:	0	0.00
Fly ash:	0	0.00
Ash:	0	0.00
b12. H_2O due to humidity:	174	9.67
N_2 with waste:	0	0.00
	-------	-----
b13. Theor. combustion products:	15140 lb/hr	513 mole/h
b14. Check (b8=b13):	15143 lb/hr	

b15. Combustion dry gas=CO_2+SO_2+HCl+N_2: 14198 lb-dry-gas/hr
b16. Combustion gas H_2O: 942 lb H_2O/hr
(b10+b11+b12)

15140 lb/hr

c. Actual Combustion Air:

Excess air rate, EAR (a8): 0.885 (assumed)

c1. O_2, additional=EAR*(Th.O_2): 2830
c2. N_2, additional=EAR*(Th.N_2): 9311
------
c3. Actual Excess dry air: 12141
c4. Excess H_2O (b5xc3): 154 lb/h
c5. Actual dry air=
theor. air+Additional O_2 and N_2 25860 lb-dry air/h

c6. H_2O associated with actual air = 328 lb H_2O
(b5xc5 or b12+c4):

c7. Actual air=dry air+H_2O in air: 26188 lb-air/h=908 lb-mole/h
(c5+c6)
c8. Air flow rate = std. volume (a10) x lb-mole/h=351305 scf/h
=(a10 x c7): =5855 scf/min

*****Test data was 3600 cfm*****

Total water vapor in flue gas
- With waste (a21): 0 lb/h
- Due to combustion (b10): 768
- Humidity (c4+b12): 328
- Quenching water: 0

------

c9. Total water vapor in flue gas = 1096 lb/hr
c10. Actual reactants=actual dry air+feed 27438 lb reactant/hr
+ H_2O in combustion air (a21+c7)= =27438 lb product/hr
Actual Combustion Products (i.e.,
Flue Gas):

c11. O_2 leftover in products = 2830 lb/hr
Additional O_2 = c1:
c12. O_2 content in flue gas = 0.1031 = 10.31%
c11 ÷ c10:
**** Test data was 10.3% ****

d. Calculation of Exit Temperature from Kiln

d1. Total heat in=Waste Heat Input (a18) + Fuel Heat Input (a19)=a20: 1.88E+07 B/h
d2. Overall heat loss (assumed as 5%, see a7): 0.0940E+07

Unburned carbon:
d3. Unreleased heat (due to unburned carbon): 0.0000E+00

Trial #1

Assumed exit temp.:	1500°F	
Reference temp.:	70°F	
d4. Temp. difference (ΔT):	1430°F	
d5. Heat in dry flue gas=$mCp\Delta T$ =[c10-c9)xa13xd4]		0.9794E+07B/h
d6. Heat in water = $mCp\Delta T$ =(c9xa14xd4):		0.0768E+07
d7. Total latent heat = (c9xa11):		0.1158E+07
d8. Heat in ash = $mCp\Delta T$=(a2xa12xd4):		0.0000E+00
d9. Total heat accounted for= (d2+d3+d5+d6+d7+d8):		1.2660E+07
d10. Net heat balance = (a20-d9)=(d1-d9):		0.6140E+07B/h

Trial #2

Assumed exit temp.:	2500°F	
Reference temp.:	70°F	
d11. Temp. difference ($\Delta T'$)	2430°F	
d12. Heat in dry flue gas=$mCp\Delta T'$ =[(c10-c9)xa13xd11]:		1.6643E+07
d13. Heat in water=$mCp\Delta T'$ =c9xa14xd11):		0.1305E+07
d14. Total latent heat=(c9xa11):		0.1158E+07
d15. Heat in ash=$mCp\Delta T'$=(a2xa12xd11):		0.0000E+07
d16. Total heat accounted for=(d2+d12+d13+d14+d15):		2.0046E+07b/h
d17. Net heat balance=(a20-d16):		-0.1246E+07b/h

d18. Using the interpolation method to estimate kiln temperature, we have:

x1	1500°F	0.6140E+07 B/Hr	y1	
	x	0.00E+00	y	y=0
x2	2500	-0.1246E+07	y2	

(x-x1)/(0-y1)=(x2-x1)/(y2-y1)

x=x1-y1(x2-x1)/(y2-y1)

d19. x= 2331°F

*****Test data was 1800°F (average kiln exit temperature)*****

SUMMARY OF CALCULATED RESULTS AND MEASURED RESULTS

Based on the calculations contained herein and information provided by the trial burn results, a summary of key data are provided in the following Table:

SUMMARY OF CALCULATED AND TRIAL BURN RESULTS

	Calculated Results	Measured Results
• O_2 content in Flue Gas	10.31%	10.3%
• Heating Value	15,045 Btu/lb	15,200 Btu/lb
• Exit Kiln Temperature	2331°F	1800°F (average)
• Air Flow Rate	5855 scfm	3600 cfm

CONCLUSIONS

The above Table shows that the differences between the calculated and the measured results are small with the exception of the kiln exit temperature and the air flow rate. The calculated value of the air flow rate is about 63% greater than the trial burn (measured) value. The difference is due to the fact that the measured air rate values neglected to account for the amount of air in- leakage which has to occur in any actual (negative pressure) kiln combustion operation. The measured data relative to oxygen content shows that the calculated air in the system (the 5855 scfm amount) is reasonable because the oxygen content measured downstream of the kiln matches the calculated oxygen concentration (the 10.3%). The calculation, therefore, confirms that the air needed is much more than the 3600 cfm measured value (which, of course, proves that air in-leakage phenomena does occur). The fact that the measured kiln exit temperature is also much lower (about 530°F lower) than the calculated kiln exit temperature indicates that the assumed amount of heat loss (the 5% figure) is probably too low.

It is hoped that these example calculations will assist those who must design incinerators or those who must know how to evaluate their performance (such as governmental permit writers, consultants and public interest groups).

REFERENCES

(EPA, 9/86), "Permit Writer's Guide Test Burn Data: Hazardous Waste Incineration," EPA/625/6-86/012, September 1986.

(Lee, 6/90), "Review of Mobile Thermal Technologies for Solid Waste Destruction," C.C. Lee, G.L.Huffman and D.A. Oberacker. Presented at the 83rd National Meeting of the Air and Waste Management Association, Pittsburgh, Pennsylvania, June 24-29, 1990.